FUNDAMENTAL FEATURE EXTRACTION METHODS FOR THE ANALYSIS OF EDDY CURRENT DATA (PREPRINT)

Jeremy S. Knopp and John C. Aldrin

Nondestructive Evaluation Branch
Metals, Ceramics & Nondestructive Evaluation Division

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14. ABSTRACT
The objective of this paper is to explore features in eddy current data that are sensitive to defects in airframe structures while invariant to other noise factors commonly encountered in nondestructive evaluation (NDE). In particular, one goal is to detect and quantify corrosion-induced material loss in multi-layer aircraft structures. To investigate this problem, a series of eddy current studies were performed using an analytical model for varying total subsurface thickness loss (6%, 8%, and 10%), and percentage of the thickness loss occurring in the first or second layer (0, 25, 50, 75, and 100%). Results for the simulated studies with varying frequency are presented. A novel feature involving the first and second order derivatives of the real and imaginary parts of the impedance with respect to frequency is presented. Another goal is to detect and quantify subsurface cracks around fastener holes in structures. To investigate this problem, a series of studies are conducted using numerical models and then empirical data sets are analyzed to verify the viability of feature extraction techniques developed through the use of modeling. A feature sensitive to subsurface cracks around fastener holes is shown. Studies are conducted to show that this feature is invariant to irregular.

15. SUBJECT TERMS
Feature extraction, cracks, material loss

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Fundamental Feature Extraction Methods for the Analysis of Eddy Current Data

Jeremy S. KNOPP[a,1] and John C. ALDRIN[b]

[a] *Air Force Research Laboratory, USA*
[b] *Computational Tools ,USA*

Abstract. Features are investigated in eddy current data that are sensitive to corrosion and fatigue cracks in airframe structures while invariant to other NDE noise factors. To investigate subsurface corrosion characterization at the faying surface, a series of eddy current studies were performed using an analytical model for varying total subsurface thickness loss and percentage of the thickness loss occurring in each layer. Results for the simulated studies are presented demonstrating a novel feature for corrosion characterization using first and second order derivatives of the impedance response with respect to frequency. For characterization of subsurface cracks around fastener holes in structures, numerical simulations and experimental studies are presented. Unique features in the measurement response in circumferential direction were found to be sensitive to subsurface cracks around fastener holes and invariant to irregular geometric factors such as fastener fit and probe tilt. Multifrequency eddy current data combined with circumferential (spatial) measurement features were found to be promising for characterizing subsurface cracks in terms of length and depth.

Keywords: eddy current, feature extraction, material loss, cracks

Introduction

The detection and characterization of subsurface cracks and corrosion in multi-layer airframe structures is a common practical problem and also a challenging research problem in NDE. Eddy current and ultrasonic methods have been applied with some success for detecting and quantifying damage. Reliable second layer crack detection using eddy current is still in its infancy [1,2]. Dual frequency eddy current techniques have been shown to be effective in detecting second layer corrosion even in cases

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where there is a variable air gap between layers [3]. Pulsed eddy current with giant magnetoresistive (GMR) sensors in conjunction with advanced data processing has also been used to detect and estimate some properties of subsurface corrosion [4]. Likewise, GMR sensors and advanced feature extraction techniques have been employed to detect subsurface cracks around fastener holes [5,6]. On-board in-situ eddy current sensors have also been considered [7].

Although an asymmetric response observed for a hole feature in an eddy current image from 2D raster scan data is typically used to distinguish crack and no crack conditions, there are a variety of potential sources of coherent noise features that produce similar asymmetric responses. In particular, misdrilled holes cause the fasteners to be skewed and irregular gaps to exist between the fastener and the hole. Variability in probe lift-off related to the scanning system hardware alignment or part surface conditions can cause variability in the signal. The consistency of windings in eddy current probes due to difficulty in manufacturing can also be a source for measurement asymmetry. Lastly, the response from adjacent fastener sites can mask an asymmetric response due to a crack. Clearly, the presence of coherent noise can increase false call rates, limit crack detectability, and ultimately decrease the prospects for crack sizing. Thus, there is a need to develop advanced data analysis approaches and find reliable features that are sensitive to the crack condition yet invariant to such coherent noise signals also present in real data.

The use of invariant features has been shown to be valuable for other problems in eddy current nondestructive evaluation. A basic approach to reduce sensitivity to liftoff during EC measurement of surface breaking cracks concerns adjusting the phase during calibration so as to isolate liftoff to the horizontal measurement component while a threshold is applied to the vertical measurement component in order to make a call. Advanced feature extraction methods have also been developed to address a wide variety of problems. For example, feature extraction methods were developed to address unknown permeability variation through an invariance transformation of flux density measurements incorporating radial basis functions [8]. The performance of neural network classifiers were found to significantly benefit from the use of such invariant signal features.

This paper focuses primarily on two concepts related to feature extraction in eddy current NDE. The first concept concerns the use of multifrequency analysis of eddy current data. In particular, a novel feature involving the second derivative of the reactance component of the impedance change with respect to frequency is investigated. The second concept concerns the use of a feature related to circumferential gradients in the reactance component at a particular radius from the center of an embedded cylinder. These two concepts are essentially applied to estimate parameters related to the aspect ratio of subsurface cracks at fastener holes.

1. Frequency Domain Feature Extraction for Characterization of Thickness and Depth of Material Loss

A series of simulations using the analytical solution for layered media were performed varying total subsurface thickness loss, and depth of the thickness loss as illustrated in Figure 1. Several different features were discovered that can be used to determine total thickness loss and depth. Figure 2(a) shows the real part of the change in impedance as

a function of frequency for a variety of thicknesses and depths. At approximately 1.5 KHz, "bands" form that provide a good measure of total thickness loss. This measure is also insensitive to the depth of the loss. Figure 2(b) shows a similar plot of the imaginary part of the change in impedance as a function of frequency. For a particular thickness loss, the imaginary component decreases as the depth of the air gap increases. Figure 3 shows the second derivative of the imaginary component of the change in impedance as a function of frequency. Again, "bands" are visible that provide a good measure of total thickness loss as observed for the real part of the change in impedance.
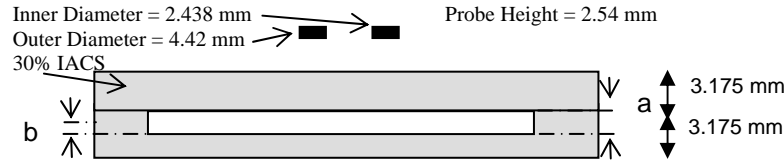

Figure 1. Diagram of two layer system with material loss at the faying surface.
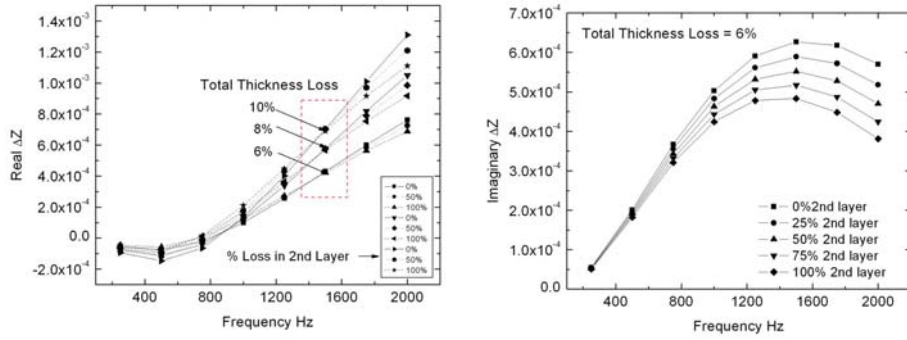

Figure 2. (a) Resistance and (b) reactance component for varying percent material loss (6%,8%,10%) and percent of material loss in 2nd layer (0%, 50%, and 100%).
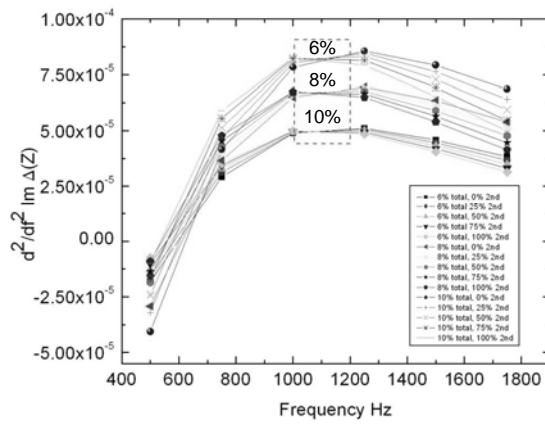

Figure 3. Second derivative of reactance component for varying percent material loss (6%,8%,10%) and percent of material loss in 2nd layer (0%, 25%, 50%, 75%, 100%).

2. Spatial Domain Feature Extraction for Improved Crack Detection

Recently, the difficult problem of distinguishing crack responses from other non-flaw asymmetric features, gaps between the fastener and hole, probe liftoff variation, and probe skew, was investigated [9,10]. The fruit of this investigation was a promising feature that is invariant to several irregular non-flaw conditions listed in the introduction to this paper. Earlier work proposed a method to determine optimal probe location for crack detection around a fastener hole [9]. Once the probe location is determined, data is collected, and if necessary, interpolated at a fixed radius around the center of the fastener site. Figure 4(a) shows the imaginary component of the change in impedance as a function of the polar angle around the fastener hole. The noticeable Gaussian shaped response is the feature that is used for crack detection. To obtain a measure of this localized crack feature, an approach was developed using a fit of a characteristic function

$$f(\theta) = A\cos(\theta) + B\exp(-D\theta^2) + C \qquad (1)$$

through nonlinear least squares estimation where the localized Gaussian response, B, can be used as a crack measure separate from the sinusoidal noise feature as shown in Figure 4(a). A model-based optimization approach was implemented to evaluate the best signal processing algorithm design to distinguish crack size. In addition, experimental studies were performed to further explore the reliability of this feature in the presence of experimental noise and adjacent holes in close proximity. Through the development of an automated algorithm to quantify this feature, results in Figure 4(b) for the experimental study demonstrate the ability to detect small cracks around fasteners while maintaining a low false call rate [10].

Although the proposed circumferential feature extraction methodology is beneficial for distinguishing crack features in the presence of certain asymmetric hole features, liftoff and probe tilt, other complex features of aircraft structures can hinder the direct application of the approach. For general inspections, the presence of adjacent fastener sites and part edges in close proximity can hinder the detection of cracks located at certain angular locations around the hole of interest. In addition, they can also contribute to the eddy current response in crack regions and thus decrease
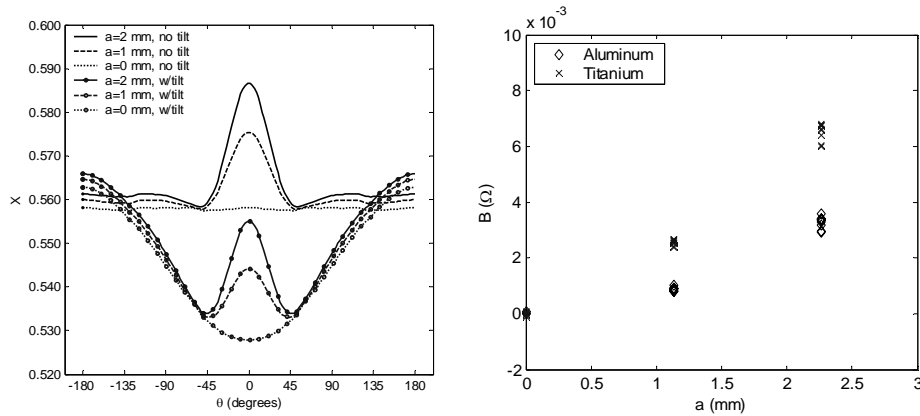

Figure 4. (a) Gaussian response due to crack shown in the presence of coherent noise and (b) simulation results show relationship between crack size and B parameter.
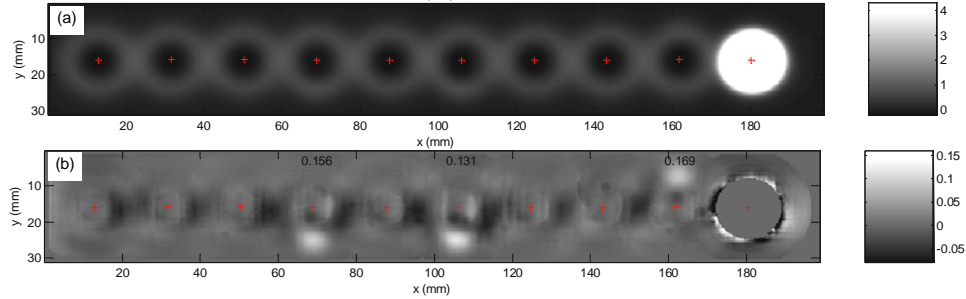
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Figure 5. Image plots of (a) original measurement data for in-phase component (V_x) and corresponding (b) processed data with hole and edge feature extraction.

prospects for sizing. There is a clear need for model-based feature extraction schemes that also compensate for adjacent fastener sites and part edges. New feature extraction methods were developed to address fitting approximate models to data associated with geometric part features including adjacent fastener sites and panel edges. The solution strategy focuses on three steps: 1) a heuristic approach using a physical understanding of the sources of greatest error, 2) a least-square estimation approach to solving for the polynomial response quickly and accurately, and 3) an iterative approach to improve model solutions for overlapping fastener site and part edge regions. Figure 5(a) displays an image plot of the original measurement data for the in-phase component (V_x) containing 10 fastener sites (9 of titanium, 1 of steel). Figure 5(b) displays an image plot of the processed data with both hole and part edge feature extraction. For this specimen with three cracks located around fastener sites, the crack features are clearly observed. A complete automated process performs this feature extraction algorithm in approximate 60 sec for a 10 hole panel, providing far greater accuracy and a 10X improvement in speed over prior experience with direct global estimation methods [11].

3. Model-based Data Analysis in Spatial and Frequency Domains for the Fastener Crack Problem

In order to fully characterize sub-surface corner cracks at fastener sites in multilayer structures, additional measures with sensitivity to all important crack dimensions are needed. In particular, the sizing of corner cracks initiating from the near surface of the second layer shown in Figure 6 requires values in the measurement data that are well correlated to varying crack length (*a*) and crack depth (*b*). Multifrequency eddy current methods have been investigated for many NDE applications that require the characterization of various damage states from part characteristics of varying depth [12]. Multifrequency eddy current data have also been used with imaging [13] and inversion methods [14,15] to improve the detection and characterization of cracks and corrosion conditions. In this work, a model-based feature extraction method of the eddy current response in the spatial domain is coupled with multifrequency data analysis for improved sensitivity to corner crack size and aspect ratio. To obtain measures with sensitivity to the localized crack dimensions, the approach uses a fit of a characteristic function for a fastener site and radial crack:
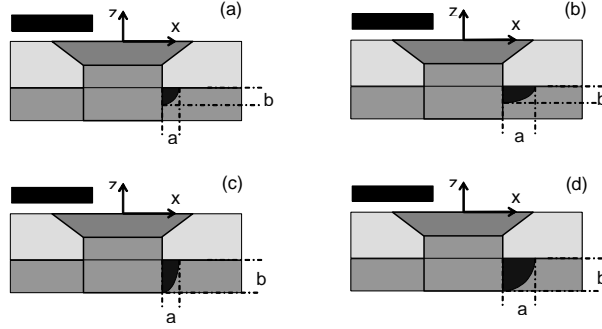
Figure 6. Diagram of fastener crack problem with varying notch length and depth: (a) a = 1.27 mm, b = 1.27 mm, (b) a = 2.54 mm, b = 1.27 mm, (c) a = 1.27 mm, b = 2.54 mm, (d) a = 2.54 mm, b = 2.54 mm.

$$f(\theta, r, f) = A(r, f)\cos(\theta) + B(r, f)\exp(-D(r, f)\theta^2) + C(r, f) \qquad (2)$$

for varying radial location and frequency. The localized Gaussian response, *B*, is evaluated as function of frequency and radial extent from the fastener site center and used as a crack measure.

To investigate the viability of this approach, simulated studies in VIC-3D® [16] were performed. Cracks were modeled as notches of finite width with a quarter ellipse profile. The crack length and depth were each varied over two levels in the study (1.27 mm and 2.54 mm) as shown in Figure 6. The frequency ranged from 50 Hz to 2000 kHz. Additional details on the probe model and multilayer structure properties can be found in prior work [10].

Figure 7 presents the simulated results for the local crack characteristic response, *B*, as a function of radial location and frequency for the four combinations of varying notch length and depth: (a) a = 1.27 mm, b = 1.27 mm, (b) a = 2.54 mm, b = 1.27 mm, (c) a = 1.27 mm, b = 2.54 mm, (d) a = 2.54 mm, b = 2.54 mm. The response as function of the radial direction provides a characteristic valley and peak moving away from the hole center. The magnitude of these local minima and maxima as a function of frequency were estimated using interpolation and investigated further for sensitivity to crack length and depth. Figure 8 presents (a) the minimum response and (b) the maximum response as a function of the frequency and the four combinations of notch length and depth. The minimum and maximum response measures are partially correlated to the cross-sectional area of the corner crack (=π*ab/4*). Both the minimum and maximum responses also exhibit some varying sensitivity to the crack length and depth with respect to frequency. Processing these minimum and maximum responses can help distinguish the crack length and depth parameters. For example, normalization of the maximum response with respect to the minimum response [as in Figure 8(c) at lower frequencies] and the maximum response at 500 Hz [as in Figure 8(d) at higher frequencies] provides the means to distinguish the two levels of crack depth. A combination of these feature measures can thus be used to help distinguish between these classes of crack length and depth and provide promise for accurate crack sizing.
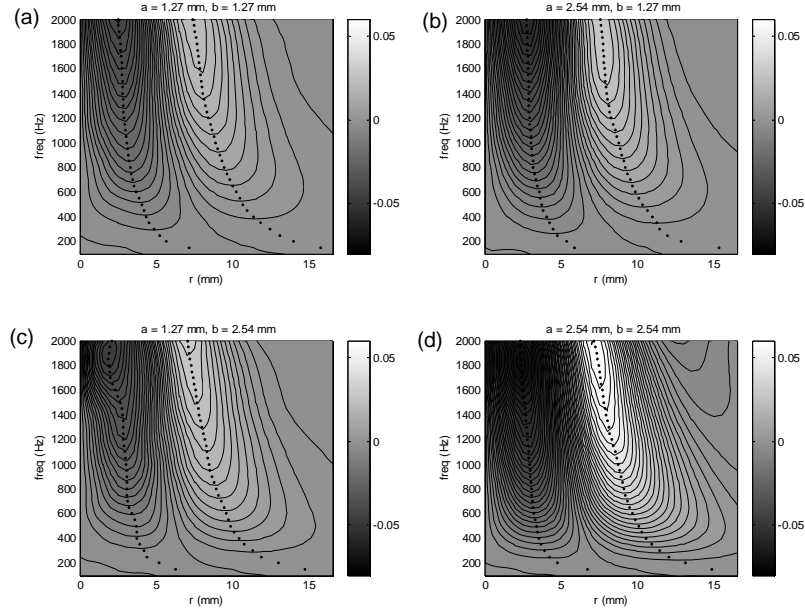
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Figure 7. Local crack characteristic response as a function of radial location and frequency for varying notch length and depth: (a) a = 1.27 mm, b = 1.27 mm, (b) a = 2.54 mm, b = 1.27 mm, (c) a = 1.27 mm, b = 2.54 mm, (d) a = 2.54 mm, b = 2.54 mm.
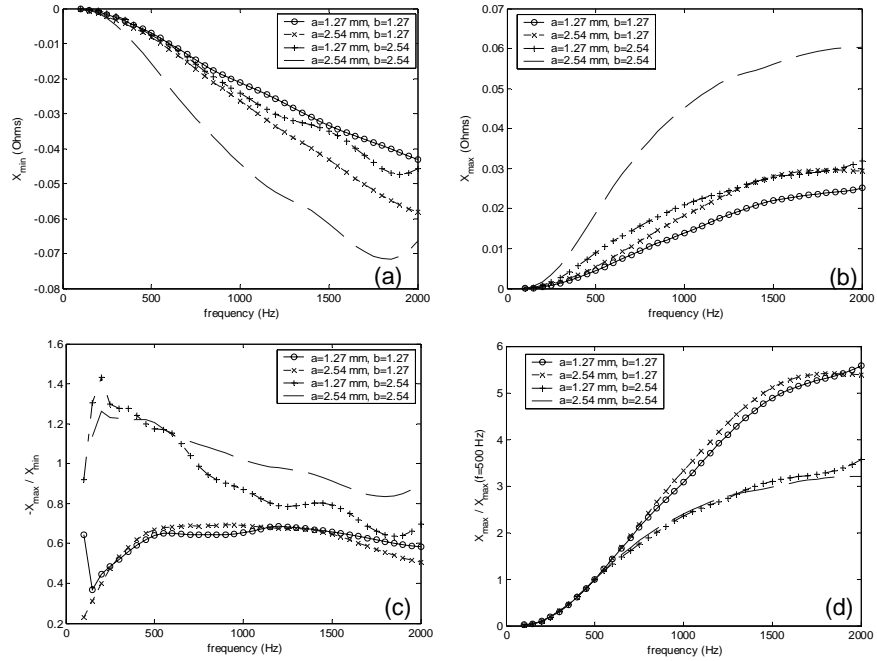

Figure 8. Calculated response with respect to frequency for varying notch dimensions representing (a) the miniumum response, (b) the maximum response, (c) the ratio of maximum to minimum responses, (d) the normalized maximum response (with respect to maximum response at 500 Hz).

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4. Conclusions And Recommendations

Features have been demonstrated to quantify subsurface material loss, detect subsurface cracks around fastener sites, and estimate parameters related to subsurface cracks around fastener sites. Experimental studies will be conducted to study the impact of measurement noise on second derivative features.

5. Acknowledgements

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